Advances in Water Resources 96 (2016) 354–372

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

A general gridding, discretization, and coarsening methodology for modeling flow in porous formations with discrete geological features

M. Karimi-Fard*, L.J. Durlofsky

Department of Energy Resources Engineering, Stanford University, Stanford, CA 94305-2220, United States

ARTICLE INFO

Article history:
Received 8 March 2016
Revised 30 July 2016
Accepted 30 July 2016
Available online 1 August 2016

Keywords:
Mesh generation
Fractures
Finite-volume method
Discrete feature modeling
Upscaling
Dual-continuum model

ABSTRACT

A comprehensive framework for modeling flow in porous media containing thin, discrete features, which could be high-permeability fractures or low-permeability deformation bands, is presented. The key steps of the methodology are mesh generation, fine-grid discretization, upscaling, and coarse-grid discretization. Our specialized gridding technique combines a set of intersecting triangulated surfaces by constructing approximate intersections using existing edges. This procedure creates a conforming mesh of all surfaces, which defines the internal boundaries for the volumetric mesh. The flow equations are discretized on this conforming fine mesh using an optimized two-point flux finite-volume approximation. The resulting discrete model is represented by a list of control-volumes with associated positions and pore-volumes, and a list of cell-to-cell connections with associated transmissibilities. Coarse models are then constructed by the aggregation of fine-grid cells, and the transmissibilities between adjacent coarse cells are obtained using flow-based upscaling procedures. Through appropriate computation of fracture-matrix transmissibilities, a dual-continuum representation is obtained on the coarse scale in regions with connected fracture networks. The fine and coarse discrete models generated within the framework are compatible with any connectivity-based simulator. The applicability of the methodology is illustrated for several two- and three-dimensional examples. In particular, we consider gas production from naturally fractured low-permeability formations, and transport through complex fracture networks. In all cases, highly accurate solutions are obtained with significant model reduction.

1. Introduction

The presence of discrete features such as fractures, faults and deformation bands within subsurface formations can have a major impact on fluid flow. The detailed understanding of flow in such systems is of interest in a variety of engineering fields. Environmental applications include aquifer management, hazardous waste disposal, and CO_2 sequestration. In the energy sector, oil and gas recovery, and the exploitation of geothermal reservoirs, often involve flow in fractured systems.

For any of these applications, specialized modeling tools – from characterization of the geology to the construction of the flow simulation model – are needed to generate accurate predictions. The geological characterization of fractured formations is very challenging and is not the focus of this work. Here we assume that an explicit and deterministic representation of the fracture distribution is available (if an ensemble of such distributions is provided, uncertainty in flow predictions can be quantified). Our objective is to integrate all of the geological data into an efficient flow simulation model. More specifically, in this paper we present a comprehensive methodology that includes grid construction, finite-volume-based numerical discretization, and flow-based model coarsening (upscaling).

The construction of a flow simulation model from a geological description can be decomposed into several steps. First, the geology is represented geometrically on a grid. As we are interested in the explicit representation of fractures and faults, a flexible unstructured approach is adopted. The geometrical representation of fracture networks is itself a challenge. A brief overview of existing techniques will be presented when we describe our specialized approach. Then, the flow equations are discretized on the unstructured grid, on which the geological features are represented explicitly. A variety of techniques have been applied for flow simulation in porous media with discrete fractures using both finite-element and finite-volume methods. Within the finite-element framework, the standard Galerkin formulation (Baca et al., 1984; Juanes et al., 2002; Karimi-Fard and Firoozabadi, 2003; Kim and Deo, 2000), the mixed finite-element method (Erhel et al., 2009; Hoteit and Firoozabadi, 2008; Ma et al., 2006; Martin et al., 2005) and the

---

* Corresponding author.
E-mail address: karimi@stanford.edu (M. Karimi-Fard).

http://dx.doi.org/10.1016/j.advwatres.2016.07.019
0309-1708/

discontinuous Galerkin method (Eikemo et al., 2009; Hoteit and Firoozabadi, 2005) have been used to simulate single-phase and multiphase flow in discrete fracture models. Within the finite-volume framework, formulations have been presented by, e.g., Bogdanov et al. (2003b), Granet et al. (2001), Karimi-Fard et al. (2004), Monteagudo and Firoozabadi (2004), Nœtinger (2015), and Reichenberger et al. (2006). A hybrid approach combining the finite-element method for the pressure equation and the finite-volume method for transport has also been investigated (Geiger et al., 2009; Matthäi et al., 2007; Nick and Matthäi, 2011).

As noted earlier, in this work we apply a finite-volume-based methodology. We proceed in this way for several reasons. In addition to its simplicity, the finite-volume approximation is very flexible in terms of control-volume shape. This enables us to apply the same discretization concept at the coarse level as at the fine level. The finite-volume technique used in this work is an enhanced version of the discrete feature model (DFM) originally developed by Karimi-Fard et al. (2004). The method applies a two-point flux approximation and entails a grid optimization step that improves grid orthogonality by shifting the locations of the pressure unknowns.

Depending on the application, if a large number of features are modeled explicitly, the resulting discrete model could be too large for practical flow simulations. Simplified models based on effective properties have been used to address this problem. Many of these techniques were developed for highly-fractured formations with high fracture connectivity. Such techniques are based on the concept of dual-continuum models, and they typically entail idealized representations of the fracture distribution (Barenblatt et al., 1960; Cai et al., 2015; Gilman and Kazemi, 1988; Kazemi et al., 1976; Pruess and Narasimhan, 1985; Warren and Root, 1963). The fluid exchange between the matrix and fracture is modeled using a transfer function. This approach has been generalized by introducing the concept of multi-rate-mass-transfer (MRMT) to account for more flow physics and formation heterogeneity (Babey et al., 2015; Di Donato et al., 2007; Geiger et al., 2013; Haggerty and Gorelick, 1995).

We are interested here, however, in the construction of coarse models from realistic (nonidealized), geometrically complex fracture distributions. Equivalent absolute tensor-permeabilities for such systems have been computed using analytical (Oda, 1985; Snow, 1969) and numerical methods (Bogdanov et al., 2003a; Koudina et al., 1998; Landereau et al., 2001; Lang et al., 2014; Nœtinger and Jarrige, 2012; Sævik et al., 2014). These procedures are for single (rather than dual) continuum representations. Single-continuum models of fractured formations are appropriate in two types of systems — when the matrix contribution to flow is negligible (very low matrix porosity and permeability), or when the fractures are sparse and not extensively connected. For many (if not most) problems of practical interest, however, these assumptions are not valid. In such cases, a dual-continuum approach, such as that applied by Bourbiaux et al. (1998), Karimi-Fard et al. (2006), Ding et al. (2006), Gong et al. (2008), and Matthäi and Nick (2009), is required to accurately represent the equivalent (upscaled) system.

In this work we present a general and systematic methodology to construct flow simulation models for complex geological formations. In contrast to existing treatments, our approach is general in that there are no assumptions or restrictions on the fracture distribution, degree of fracture connectivity, or matrix properties. Thus, the same general approach is applicable for a wide range of systems, from highly fractured formations to heterogeneous porous media with few or no fractures. This flexibility is very important for practical problems, as different parts of a formation can have quite different characteristics. Our new methodology can also account for sealing or low-permeability features, such as deformation bands, within the same general framework.

This paper proceeds as follows. We first present a specialized gridding procedure for the geometrical representation of discrete geological features such as faults and fractures. Then, a finite-volume discretization technique that is applicable for such models is presented, along with a grid optimization procedure that reduces the error in the two-point flux approximation. Model coarsening, which entails aggregation of fine-grid cells and the flow-based computation of coarse-scale flow parameters, is then described. Fine and coarse-scale numerical results for several challenging two and three-dimensional problems, which involve natural and engineered fractures, are then presented. A two-phase flow example is considered in the Appendix.

We note that earlier versions of some of the procedures within our overall methodology have been presented in earlier papers or conference proceedings. Of the main components of the framework, only the discretization has been presented previously in full detail. The general gridding procedure has not been presented, and the aggregation-based upscaling has only been discussed within more limited settings. The examples presented in this work are all new and highlight the capabilities of the full methodology.

2. Geometrical representation of a set of intersecting surfaces

The generation of grids honoring complex internal geometrical features is a challenging task that has been investigated in many areas of computational physics. Our focus in this section is on the geometrical representation of geological structures defined by three-dimensional surfaces; e.g., faults and fractures. We wish to rely as much as possible on existing gridding tools. The majority of available tools are designed to represent a given model as accurately as possible. This is an important characteristic in many engineering applications, though with geological models the exact location of discrete features is often somewhat uncertain. In fact, practical models are commonly generated using geostatistical approaches (Golder Associates, 2012). This motivates the use of procedures that do not exactly honor all aspects of the initial geometrical description.

Although the problem of computing the exact intersection between a set of surfaces is mathematically well posed, there are practical problems depending on the relative positions of the surfaces. These problematic configurations are well known and have been documented (Holm et al., 2006; Reichenberger et al., 2006). They can be summarized into situations where surfaces are in “close” proximity and/or are “slightly” overlapping. An exact representation of these configurations often leads to excessive degrees of local grid refinement. This issue can become intractable for large systems with many of these problematic configurations. An example of exact meshing for a fracture network can be found in Koudina et al. (1998), where the fractures are represented by planar polygons. This type of technique can, however, only be applied to cases without problematic configurations (or to systems where the problematic configurations have been discarded using the feature rejection algorithm proposed by Hyman et al. (2014)).

A way to overcome the geometrical difficulties associated with problematic configurations, without removing them entirely from the model, is to introduce some changes in the geometry of the surfaces. The basic assumption with this treatment is that these changes will not have a significant impact on flow quantities of interest. We expect this to be the case when the fracture connectivity is maintained, and this is accomplished with our method. We now review some of the relevant grid generation techniques, after which we describe our approach in detail.

2.1. Review of relevant gridding techniques

One of the earliest studies on the gridding of a fracture network using geometrical simplification was presented by